NASA Tech Briefs

National Aeronautics and
Space Administration

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Electronic Systems

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INTRODUCTION

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National Aeronautics and Space Administration

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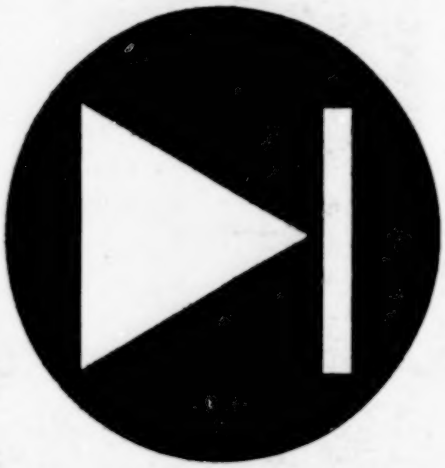

Electronic Components and Circuits

Hardware, Techniques, and Processes

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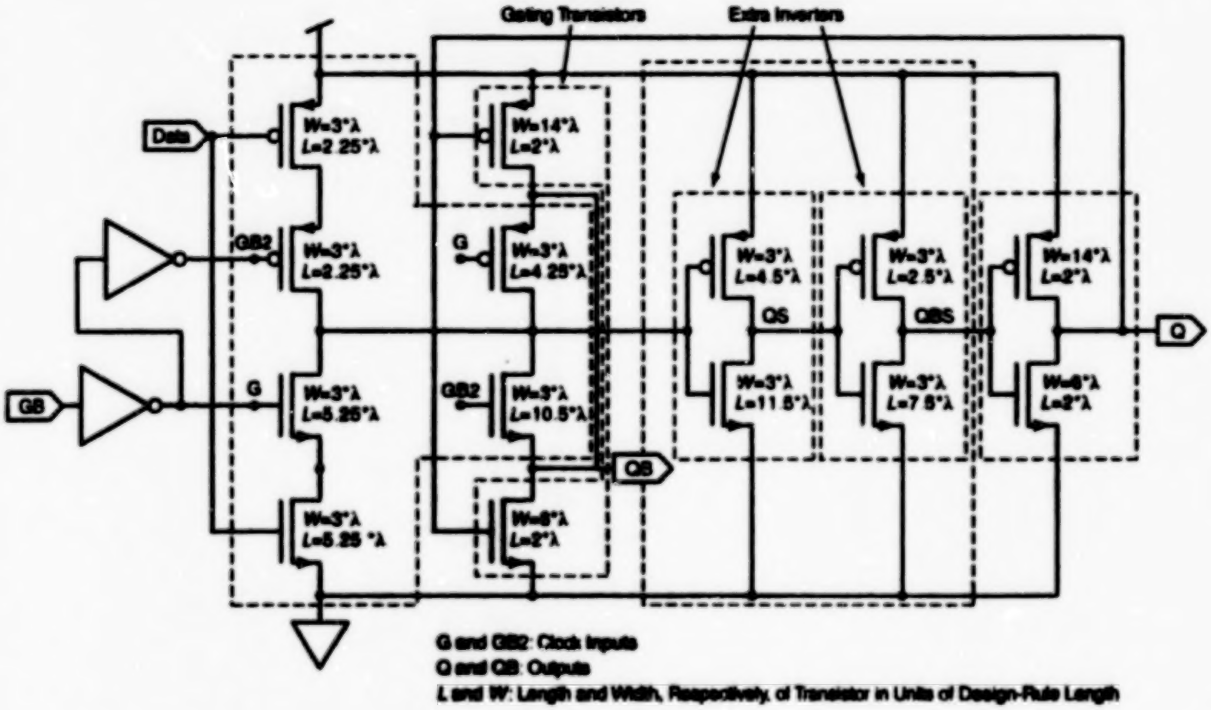
SEU-Tolerant Flip-Flops

These circuits could be fabricated on commercial CMOS process lines.

Lyndon B. Johnson Space Center, Houston, Texas



This Compact SEU-Immune Flip-Flop Circuit would be almost completely immune to SEU. The two extra inverters together with the normal gating transistors provide three independent delay stages for absorbing glitches, the minimum theoretically required. Glitches are absorbed whether generated internally, or whether coming in on the Data or clock (GB) lines, as long as the timing guidelines are followed. What is shown is a latch, which is 1/2 of the common D-flip-flop circuit.

Several improvements in the designs of flip-flop circuits that are parts of logic circuits have been proposed to reduce the incidence of logic errors associated with single-event upsets (SEUs) [bit flips caused by incident energetic ionizing particles]. Traditionally, radiation-hardened integrated circuits have been manufactured on special process lines, with emphasis, variously, on immunity to latchups and SEUs for outer-space applications or on total-dose hardness for military applications. The present improvements are intended to confer latchup and SEU immunity of a degree and type suitable for outer-space applications, but unlike in the traditional approach, the improved designs could be implemented on ordinary commercial complementary metal oxide semiconductor (CMOS) process lines.

A complete description of the proposed improvements and of the historical background prerequisite to understanding the improvements would greatly exceed the space available for this article; only a brief summary can be given here. Historically, guard rings have been used to prevent latchups. In theory, SEU can be eliminated via redundancy, but conventional redundancy involves at least 3 copies of all basic logic circuitry plus additional logic circuitry in the form of an infallible voter circuit. One patented scheme calls for dual redundant flip-flop circuits, called "Whitaker cells" after their inventor, in which what is known about the possible directions of upsets in n- and p-channel devices is utilized to enable the cells to recover from upsets. Numerous other prior developments involve using extra delays within the flip-flop to reduce its susceptibility to glitches. These include the addition of passive components, which are often expensive to fabricate in a logic process, or extra pairs of inverter stages. The minimum number of extra inverter stages described in prior art is 2 pair, or 4 extra inverters. There are also other non-Whitaker schemes involving dual flip-flops cross-coupled in some novel way to avoid or reduce upset.

In the dual flip-flop schemes, dual rail logic may be used to drive the pair of flip-flops. In the Whitaker schema, single rail logic may also be used, with the second flip-flop data provided through a delay equal to the worst-case glitch time for the logic family, which eliminates the possibility of a glitch arriving simultaneously on both flip-flops. The worst-case time is approximately the propagation time for a fully loaded node on the slowest gate. All gates must be designed with balanced rise and fall times for this to work. Glitches on clock lines must be avoided either by distributing clock signals separately to the two sides of the dual flip-flop, or using extra capacitances (up to 4 pF) and large drivers on all clock lines, and avoiding the generation of a clock line internally. These are very restrictive and expensive constraints. Nor do these prior developments provide for asynchronous preset and clear operations.

The proposed improvements are summarized as follows:

- Optimized transistor sizing is used to make the shortest possible delay elements in a delay-based design, without resorting to passive components or more than one extra pair of inverters within the flip-flop. This requires fewer transistors than prior delay-based designs, and far fewer than any of the dual flip-flop designs.
- Some of the delay is distributed into

existing transistors within the flip-flop in order to control the glitch times which can be generated within the flip-flop, while absorbing external data or clock line glitches.

- The same delay-based technique would be used to enable asynchronous preset and clear.
- Only one guard ring with allowed polycrystalline-silicon crossings would be used.
- Multistage balanced rise and fall times inside an ordinary flip-flop would be used to absorb glitches without changing state of the flip-flop.

Circuits that incorporate the proposed improvements could be simpler, more compact, and more functional, relative to prior SEU-immune circuits based on dual flip-flops or more costly delays. The delays involved, approximately one to two gate delay times in operation of the flip-flop, are comparable or less than the delays introduced in all prior forms of radiation-tolerant flip-flops (except the expensive and complicated case of dual flip-flops driven by dual-rail logic).

This work was done by Robert Shuler, Jr., of Johnson Space Center.

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Johnson Space Center, (281) 483-0837. Refer to MSC-22953.

Multifunction Input/Output Integrated Circuits

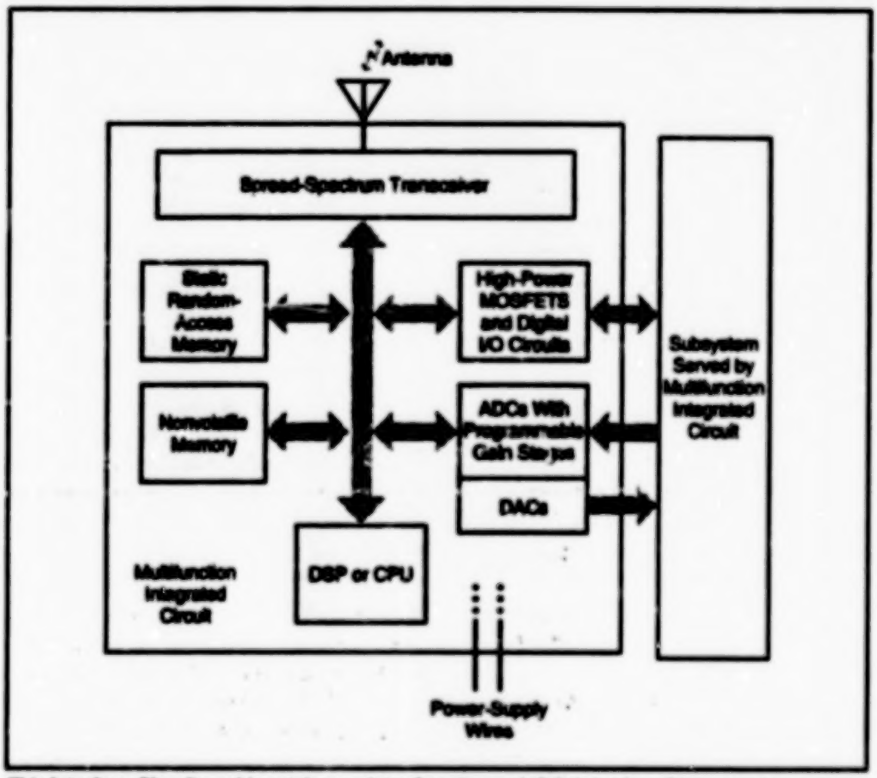
Advantages would include network fault tolerance and simplification of wiring.

NASA's Jet Propulsion Laboratory, Pasadena, California

Integrated circuits that would perform a variety of analog-signal, digital-signal, and power input/output functions have been proposed. Conceived for use as versatile, fault-tolerant interfaces among components and subsystems of spacecraft, these multifunction integrated circuits could also be attractive for similar uses in a variety of terrestrial systems, including ground vehicles, aircraft, industrial facilities, and communication systems.

Each such multifunction integrated circuit would be fabricated as a single complementary metal oxide semiconductor (CMOS) chip that would contain some or all of the following functional units (see figure):

- A transceiver for spread-spectrum radio communication with other such integrated circuits;
- A microprocessor functioning as a central processing unit (CPU) or digital signal processor (DSP);
- Volatile and/or nonvolatile memory circuits;
- Analog input circuits, including signal-conditioning amplifiers and analog-to-digital converters (ADCs);
- Analog output circuits, including digital-to-analog converters (DACs);
- Digital input/output (I/O) circuits;
- Power-switching circuits containing high-power metal oxide semiconductor field-effect transistors (MOSFETs).



This Interface Circuit would contain a variety of analog and digital circuitry, all integrated on a single chip, for performing a complete set of signal and power input and output functions for the subsystem to which it would be connected.

The multifunction integrated circuit would serve as both a power and a signal interface for the subsystem or component to which it was connected. If, for example, the subsystem were a motor, then the multifunction integrated circuit could receive motor commands transmitted by radio from a different subsystem, switch the motor power on and off as needed, and possibly transmit data on the operation of the motor (e.g., shaft-angle, speed, voltage, and/or current readings) to another subsystem. Other than wire connections for a radio-communication antenna and for the motor or other subsystem served, the only wire connections between the multifunction integrated circuit and the rest of the system would be those needed to supply power to the circuit and subsystem.

All data and control signals — both digital and analog — would be transmitted via the radio links. By serving as standardized interfaces that would eliminate the need for signal wiring, these multifunction integrated circuits could make it easier to design and construct multinode systems that could be reconfigured in software (and perhaps in hardware). With respect to digital communication among subsystems, each of the multifunction integrated circuits would constitute a node of a wireless communication network. By use of previously developed Ethernet (or equivalent) and spread-spectrum protocols, babbling (uncontrolled transmission) by one of the nodes of the network would be prevented from interfering with communication among the other nodes.

This work was done by James Dillon and Michael Newell of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP [see page 1].

NPO-30212

High-Temperature Coils for Electromagnets

High-temperature coils can be made more compact than before.

John H. Glenn Research Center, Cleveland, Ohio

Coiled electric wires have been developed for use in electromagnets that operate at high temperatures. Examples of such electromagnets could include the actuators in magnetic bearings in advanced gas turbines.

The primary distinction between these wires and previously commercially available high-temperature wires lies in the electrical insulation, which is intended to withstand operating temperatures in the range from 800 to 1,300 °F (≈430 to ≈700 °C). The commercially available wires feature tubular sheaths filled with insulating materials; while such insulation is effective, it is too bulky for electric-coil applications in which there are stringent limitations on the sizes of the coils and/or on the spacing between turns. The present wires feature improved insulation that is thinner, making it possible to fabricate coils that are smaller and more closely wound.

The starting wire material for a coil of this type can be either a nickel-clad, ceramic-insulated copper wire or a bare silver wire. The starting wire is either primarily wrapped with S-glass as an insulating material or else

The Connection End of a 12-Pole Magnetic Bearing is depicted here during a test at a temperature of 1,000 °F (≈540 °C) in a series of tests that ranged up to 1,200 °F (≈650 °C).

covered with another insulating material wrapped in S-glass prior to the winding process. A ceramic binding agent is applied as a slurry during the winding process to provide further insulating capability. The turns are pre-bent during winding to prevent damage to the insulation. The coil is then heated to convert the binder into ceramic.

In a test, coils of this type were mounted in a 12-pole magnetic bearing (see figure) and found to perform successfully at temperatures up to 1,200 °F (≈650 °C). Future development efforts will address the problems of increasing the thermal conductivity of the electrical-insulation materials to increase conduction of heat out of the coils, reducing the volumes of the coils, and fabrication of coils with various shapes (including square and other noncircular cross sections).

This work was done by Alan Palazzolo of Texas A&M University for Glenn Research Center. Further information is contained in a TSP [see page 1].

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17164.

"Morphing" in Evolutionary Synthesis of Electronic Circuits

The search for viable circuits can be conducted more efficiently and thus faster.

NASA's Jet Propulsion Laboratory, Pasadena, California

A method of automated evolutionary synthesis of electronic circuits has been augmented by a concept called "morphing through fuzzy topologies." Previous versions of the method provided for the evaluation of "crisp" topologies were precisely specified by open/closed (on/off) interconnection switches. The present, augmented version provides for evaluation of topologies specified by switches that support partial degrees of opening. These "fuzzy" topologies with partly open, partly closed switches have behaviors very similar to those obtained by a combination of "crisp" topologies. It is almost as if several "crisp" topologies are superimposed on each other, and are evaluated simultaneously when the fuzzy topology is evaluated. Like the previous versions, the present version is expected to enable the synthesis of a variety of digital and analog circuits with desired functional responses.

Previous, discrete-topology versions of the method were described in "Reconfigurable Arrays of Transistors for Evolvable Hardware" (NPO-20078), *NASA Tech Briefs*, February 2001; and "Evolutionary Automated Synthesis of Electronic Circuits" (NPO-20535), *NASA Tech Briefs*, July 2002. To recapitulate: "Evolution" is used here in a quasi-genetic sense, signifying the construction and testing of a sequence of populations of circuits that function as incrementally better solutions of a given design problem. The circuits are implemented either in software simulations or in hardware. Evolution in hardware involves the use of electronically reconfigurable arrays of transistors as analog switches for the selective, repetitive connection and disconnection of transistors and other circuit building blocks. The evolution is guided by a search-and-optimization algorithm (in particular, a genetic algorithm). At each step of the evolutionary process, the circuits are ranked according to how close their behaviors come to the desired behavior. A new population of circuits is generated from a selected pool of best circuits in the previous generation, subject to such genetic operators as chromosome crossover and mutation. The process is repeated for many generations, yielding progressively better circuits. The criterion for stopping the evolution can be the reduction of error below a certain threshold or reaching a predetermined number of generations.

The present, augmented method applies primarily to evolution in hardware and secondarily to software simulations in which highly accurate mathematical models of circuits are used. The hardware implementation would involve the use of field programmable transistor arrays (FPTAs), which contain T-gate transistors as analog switches. These switches differ from the switches of the discrete-topology version of the method in that instead of being limited to "on" or "off" states, their resistances would be continuously variable between low values (tens to hundreds of ohms, in the "on" state) and high values (~ hundreds of MΩ in the "off" state).

By virtue of the intermediate values of

the switch resistances, the response of a given circuit topology is almost as if one would combine the responses of several circuit topologies specified by on/off switches. The superposition of circuit topologies would be characterized as "fuzzy" because it would blur the borders among distinctive circuit topologies: the resulting circuits would belong, only to certain degrees, to discrete topologies, in each of which any two given components are either connected or not. In effect, a fuzzy topology would contain many "seeding" topologies with superimposed effects. The role of evolution would be, in part, to isolate the most promising one of the seeding topologies present. In still other words, evaluation of a fuzzy topology would be somehow equivalent to simultaneous concurrent evaluation of several superimposed circuit configurations.

The genetic algorithm would specify whether each switch would be in a low- or high-resistance state, but in a process somewhat reminiscent of annealing, the numerical meanings of "low" and "high" would change gradually as a function of a temperature-like parameter. Initially the temperature-like parameter would be high, causing the "low" and "high" switch status to have values close to each other. Gradually (typically over ~100 generations to ensure quasi-static response), the temperature-like parameter would be made to decrease, causing the switch resistances to become polarized to their extreme high ("off") and low ("on") values. This annealing-like process would induce modifications of the circuit to be evolved. The evolutionary effect of this annealing-like process is what is meant by "morphing through fuzzy topologies."

Tests both in simulations and in hardware by computational simulation have led to the preliminary conclusion that in comparison with a discrete-topology version of the method implemented with binary switches, morphing through fuzzy topologies is about an order of magnitude more efficient as a means of searching for a desired circuit topology. Promising individuals (with higher fitness) have been found much earlier in the search.

If the goal in a given situation is to obtain a discrete topology, then morphing through fuzzy topologies can accelerate evolution toward the goal. On the other hand, in some cases, the degrees of opening of the switches could be regarded as extra degrees of freedom for design problems, thereby making possible increased numbers of solutions.

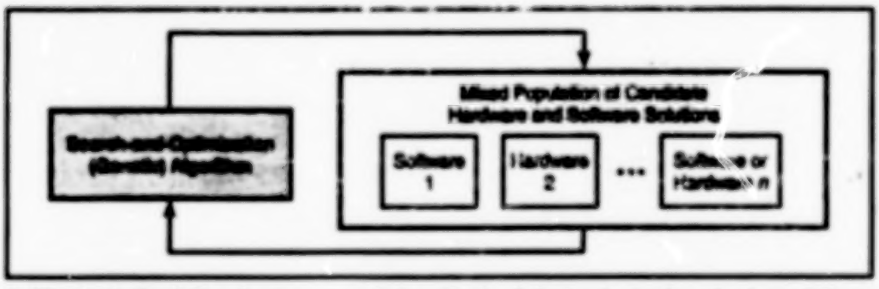
This work was done by Adrian Stoica and Carlos Salazar-Lazaro of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP [see page 1].*

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, NASA Management Office-JPL [see page 1]. Refer to NPO-20837.

Mixtrinsic Evolutionary Synthesis of Electronic Circuits

Designs are expected to be more robust and portable.

NASA's Jet Propulsion Laboratory, Pasadena, California



In Mixtrinsic Evolution for the automated synthesis of electronic circuits, mixed populations of both hardware and software are evaluated or each individual is evaluated both in hardware and in software.

A method of automated synthesis of analog and/or digital electronic circuits involves evolution in both software simulations and hardware. Heretofore, the evolutionary automated synthesis of electronic circuits has been accomplished by use of either software simulations or hardware, but not both. Evolution in software has been called "extrinsic," while evolution in hardware has been called "intrinsic." Because evolution by the present method involves both intrinsic and extrinsic elements, it is called "mixtrinsic."

Part of the trouble with software evolution is that when some evolved circuits are implemented in hardware, their behaviors differ greatly from those predicted in the simulations. Similarly, part of the trouble with hardware evolution is that some circuits evolved in hardware behave differently when they are analyzed in computational simulations. The cause of these mismatches is the limited accuracy of the mathematical circuit models embodied in the software. To some extent, the accuracy of the circuit models can be increased at the cost of increased simulation time. However, some information about circuits depends on fabrication process and cannot be included in the models. In addition, it can be desirable to evolve circuits that exhibit behaviors independent of the details of fabrication processes.

Another important and related issue is that of robustness and portability of solutions. In each case, evolution finds the "easy way out," optimizing for whichever raw material (mathematical model or hardware components) is given. The inability to port a software solution to hardware renders the software solution useless in a commercial or other practical setting. On the other hand, the inability to analyze an evolved hardware solution in a software simulation reduces confidence in the hardware intrinsic solution because the solution cannot be shown to work outside the operating region used in the evaluations during evolution.

The limited range of applicability of a solution is of special concern if the solution exploits very specific effects. Such a solution could be characterized as a "point design." What is needed is a "domain-wide" design that could constitute a solution within a large envelope of operating parameters. Examples of such parameters include temperature, power-supply voltage, and measures of ionizing radiation.

In mixtrinsic evolution, one uses populations of mixed individuals — some evaluated in software simulations and some in real hardware (see figure). In a variation of the technique, each individual is evaluated both in hardware and in software and is assigned an averaged measure of goodness. Mixed populations constrain the evolution to a solution that both perform well in hardware and can be well simulated in software. Such a solution exploits

characteristics included in the software model for producing the desired behavior but does not rely on the special characteristics of a specific hardware implementation. Solutions based on hardware properties outside the software model are eliminated by evolution, because during evolution, each solution can be randomly assigned for evaluation in either hardware or software. As a result, solutions are robust; in addition, they are likely to be patentable and in accordance with common design rules.

This work was done by Adrian Stoica of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, NASA Management Office–JPL (see page 1). Refer to NPO-20773.

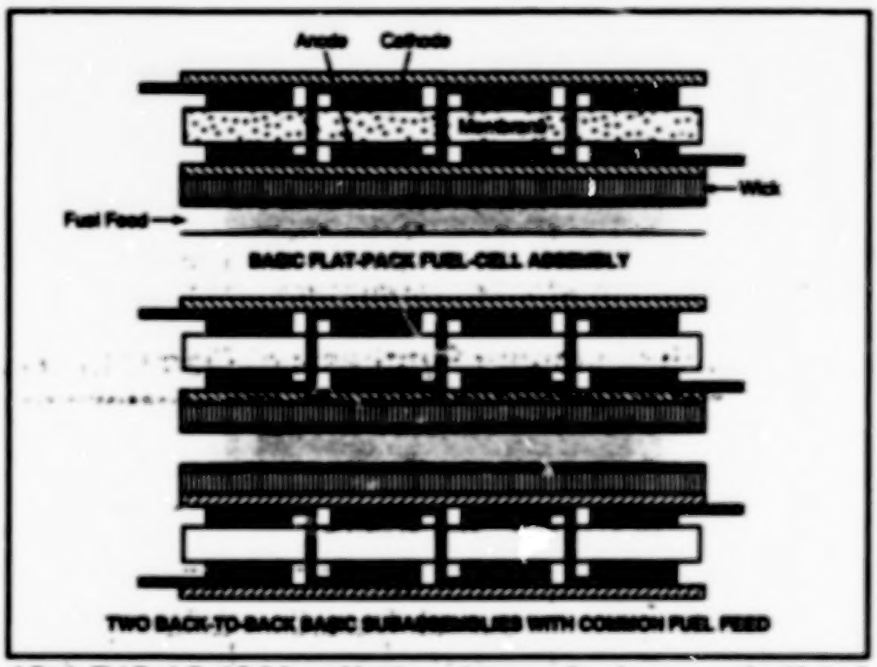
Miniature Fuel Cells for Small, Portable Electronic Devices

A significant portion of the bulk and complexity of conventional fuel cells is eliminated.

NASA's Jet Propulsion Laboratory, Pasadena, California

Miniature fuel cells in a "flat-pack" configuration are being developed as alternatives to rechargeable batteries in cellular telephones, laptop computers, and other small, portable electronic devices. These fuel cells exploit the electrochemical oxidation of organic fuel (usually methanol) in air. Whereas power sources based on state-of-the-art lithium-ion batteries have specific energies of no more than ~150 W-hr/kg, power sources based on the present developmental fuel cells are expected to have specific energies between 500 and 1,000 W-hr/kg. Moreover, whereas one must often wait for batteries to be recharged before using them, a fuel cell can be refueled and used immediately.

Conventional fuel-cell assemblies include bipolar plate stacks, pumps, blowers, and other ancillary items that not only contribute to cost but also add bulk and complexity, thereby posing considerable impediments to miniaturization. In the present developmental fuel cells, the flat-pack configuration is part of an overall improved design that eliminates much of the bulk and complexity.



A Basic Flat-Pack Fuel-Cell Assembly takes up less space than does a conventional fuel-cell assembly of the same capacity. Multiple basic subassemblies can be combined in a compact back-to-back configuration to increase capacity.

A flat-pack fuel-cell assembly can include one or more fuel cells electrically connected in series and/or parallel to obtain the required current and/or voltage rating. A typical basic flat-pack fuel-cell assembly (see figure) contains a single polymer electrolyte membrane that serves multiple cells. The cathodes of all the cells are located side by side in the same plane on one side of the membrane, while the anodes of all the cells are similarly located on the other side of the membrane. A fuel-feed manifold and a wick deliver fuel in regulated amounts to the anodes. The cathodes are exposed to air in a manner similar to that of metal/air batteries.

Series electrical connections between adjacent cells are made in the form of posts that extend through the membrane. These posts are made from such corrosion-resistant, electronically conductive materials as graphite, platinum, and/or gold, along with (if needed) an appropriate stable polymeric binder. Alternatively or in addition, parallel and/or series electrical connections among cells can be made in the form of thin edge connector plates that include segmented strip conductors made of gold or graphite.

Fabrication of a multiple-cell membrane/electrode assembly like that shown in the figure involves the application, to the membrane, of catalyst layers and backing structures for the anodes and cathodes. The techniques of fabrication include the use of catalyst inks and either the use of pre-coated electrodes or else sputter deposition of the electrodes. Gas-diffusion backing layers are preferably bonded to the membrane by hot pressing. Optionally, nonbonded backing layers can be used instead of bonded ones.

The preferred anode catalyst is Pt-Ru; the preferred cathode catalyst is Pt. The anode structure is made hydrophilic so that an aqueous solution of liquid organic fuel can readily flow to the catalyst layer and the carbon dioxide product can readily leave the anode surface. The cathode is made hydrophobic to exclude water and thereby facilitate the flow of air.

This work was done by S. R. Narayanan, T. I. Valdez, Filiberto Clara, and Frank Harvey of Caltech for NASA's Jet Propulsion Laboratory. Further information is contained in a TSP (see page 1).

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

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Refer to NPO-21066, volume and number of this NASA Tech Briefs issue, and the page number.

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Electronic Systems

Hardware, Techniques, and Processes

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Sequential-Color LED Illumination for Reflective Microdisplays

Integrated silicon microdisplays, such as liquid-crystal-on-silicon (LCOS) devices, are becoming the most effective image source for high-resolution viewfinders, head-mounted displays, and helmet-mounted displays (HMDs). Since these microdisplays are reflective in nature, they require new arrangements of illumination and viewing optics compared to previous transmissive displays. A complete display might comprise a reflective microdisplay panel lit from the front, through a beam splitter, by a light-emitting-diode (LED) illuminator, and viewed through an eyepiece optic. Full-color display, without resolution-degrading color filter triads, can be achieved with one simple microdisplay panel by utilizing field-sequential color — easily attained by making the illuminator from a few red, green, and blue LEDs. The best image quality is provided, though, when the illuminator appears as an extended diffuse white spot, rather than red, green, and blue points. This can be achieved by spacing a diffuser between the LEDs and the display, with the light from the differently colored LEDs overlapping on the diffuser to make a white spot. An especially efficient arrangement is achieved with a specularly reflecting microdisplay when the illuminator and eyepiece lens are positioned so that the lens simultaneously makes a virtual image of the display panel, and a real image of the illuminator. By arranging the image of the illuminator to fall in the same position as the pupil of the viewer's eye, the largest possible amount of illumination light is made usable by the viewer, while the amount wasted is minimized. For microdisplays that operate in polarized light, high optical efficiencies are obtained if the needed beam splitter is a polarizing beam splitter (PBS). The overall system can be simplified if the PBS is curved, which saves space and combines the function of an illuminator condenser or collimating lens. PBS function can also be obtained from suitable edge-illuminated holographic illuminators.

This work was done by Mark Handschy, Mike Meadows, and Holden Chase of Displaytech, Inc., for **Johnson Space Center.**

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

Displaytech, Inc.
2602 Clover Basin Drive
Longmont, CO 80503-7603
Tel. No.: (303) 772-2191
Fax No.: (303) 772-2193

Refer to MSC-22990/91, volume and number of this NASA Tech Briefs *issue, and the page number.*

Console for an Overhead-Bridge Crane

Human factors engineering has been applied to the design of an overhead-bridge crane control console for use by a seated operator in a clean-room environment. The crane console provides the operator with the ability to lift and move loads up to 27.5 tons (24.9 tonnes) in three vertical speed ranges and three horizontal speed ranges with a horizontal and vertical positioning accuracy of 0.010 in. (0.25 mm) and 0.005 in. (0.13 mm), respectively. The design, to be used with radio communication, provides the operator with information on position, velocity, and crane functioning, allowing the operator to move the load precisely while having no visibility of the crane hook (a unique Kennedy Space Center requirement that necessitated a wavier from a Federal safety regulation). The console dimensions and seating provide adjustability to accommodate 90 percent of the population and minimize the risk factors associated with fatigue and cumulative trauma disorders. The controls and displays were selected to optimize human performance. They were arranged according to functional groups, sequence, and frequency of expected use and positioned to optimize reach, visibility, and legibility. The systematic application of human factors engineering principles throughout the design process will reduce the probability of human error during operations and maintenance, thereby increasing overall safety in crane operations.

This work was done by Faith T. Chandler and William D. Valentino of The Boeing Company, for **Kennedy Space Center.** *Further information is contained in a TSP* *[see page 1].*

Inquiries concerning rights for the commercial use of this invention should be addressed to the Technology Programs and Commercialization Office, Kennedy Space Center, (321) 867-4879. Refer to KSC-12279.

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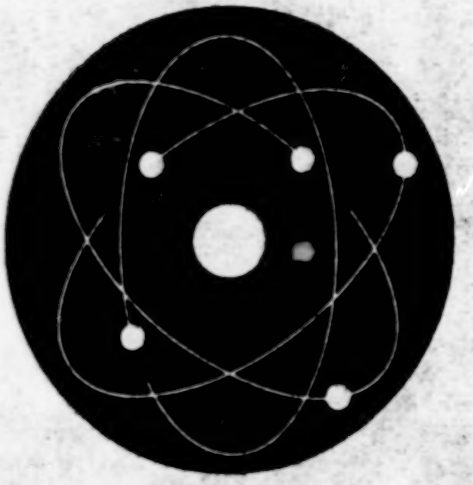

Physical Sciences

Hardware, Techniques, and Processes

Books and Reports

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Temperature-Compensation Method for High-Temperature Strain Gauges

Strain gauge and temperature-compensation element are exposed to the same temperature.

Dryden Flight Research Center, Edwards, California

Figure 1. The Active Strain Gauge and the Temperature-Compensation Element are labeled "RActive" and "RComp," respectively. The straps that hold down the compensation element have been removed, and the gauge has been lifted for this photograph. Contact with the substrate must be maintained to ensure thermal conduction in the presence of transient heating.

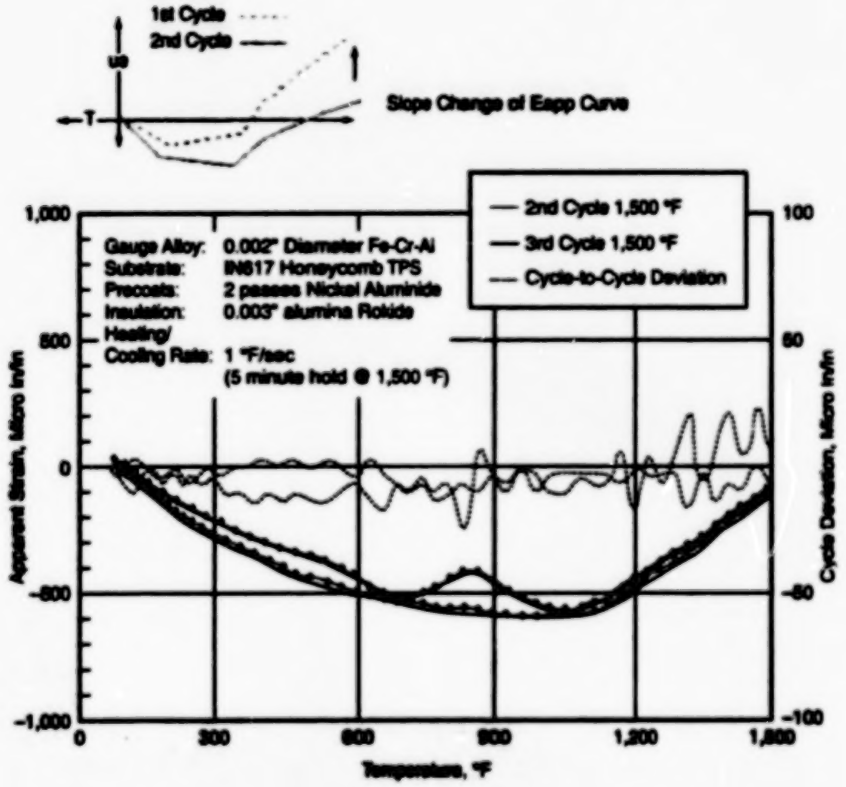


Figure 2. These Apparent-Strain Curves obtained by a half-bridge strain gauge utilizing the presented temperature-compensation element exhibit little zero shift, a low rate of drift at 1,500 °F (~820 °C), less nonlinearity (in comparison with uncompensated strain gauges), a high degree of cycle-to-cycle repeatability, and no cycle-to-cycle slope changes.

A relatively simple and inexpensive method of fabricating a temperature-compensation element for high-temperature strain gauges has been devised. This element, connected in the adjacent arm of a Wheatstone bridge, provides temperature compensation for an active strain gauge attached to the substrate. A method for accurately measuring structural static strains in harsh environments is an important requirement for future flight research of hypursonic vehicles and ground test articles. Sturdy, flight-worthy strain sensors must be developed for attachment to superalloys, new composite materials, and thermal-protection systems. With little deviation from standard Rokide flame-spray installation procedures, preliminary tests indicate viable data can be produced to operating temperatures of at least 1,700 °F (927 °C).

In the present method, the temperature-compensation element is encapsulated and insulated in alumina by the Rokide flame-spray process and used as an inactive element in a half-bridge configuration. An inactive element, or gauge, is often also referred to as a "dummy gauge" because it does not sense surface strains; in other words, there is no mechanical strain transfer from the substrate to the gauge filament. The temperature-compensation element is mounted in close proximity to the attached, or active, strain gauge. Adequate surface contact of the compensation element to the test article must be achieved in order to maintain good thermal conductivity. However, unlike the active strain gauge, the temperature-compensation element is not rigidly attached to the substrate which is to be measured; instead, the temperature-compensation element (see Figure 1) is attached flexibly to the substrate using nickel/aluminum-alloy straps.

Configured as a half-bridge, the temperature-compensation element is connected in an arm of a Wheatstone bridge adjacent to an arm containing the active strain gauge. The temperature-compensation element does not sense mechanical surface strains, but it is subjected to the same temperatures as is the active strain gauge. Inasmuch as equal changes in adjacent arms of a Wheatstone bridge cancel, the equal temperature-induced components of the changes in the resistance of the active strain gauge and the temperature-compensation element cancel, leaving a Wheatstone-bridge output indicative of only the surface strain in the substrate.

The Flight Loads Laboratory at NASA Dryden Flight Research Center has evaluated and characterized many high-temperature strain-gauge assemblies over the years, maintaining rigorous focus on reducing the thermal output, or apparent strain, of these gauges. High-temperature strain-gauge alloys generate outputs indicative of large magnitude, nonlinear, apparent strains that depend on maximum operating temperature, time at temperature, and rates of cooling. The apparent-strain output of a high-temperature strain gauge consists of three main components: (1) the mismatch in coefficients of thermal expansion between the substrate and the gauge alloy, (2) the thermal coefficient of electrical resistivity of

the gauge alloy, and (3) the change in gauge factor as a function of temperature. Characterization of strain gauges at elevated temperatures is critical inasmuch as correction curves must be generated and applied to raw data to determine true mechanical strains from indicated strains.

Prototype temperature-compensation elements, according to the present method, were wired with active high-temperature strain gauges as half-bridges. Both the temperature-compensation element and the active strain gauge were made of 0.002-in. (0.05-mm) Fe/Cr/Al-alloy wire. The active strain gauge was attached and insulated to the substrate using standard NASA Dryden plasma spray (precoat) and Rokide flame-spray procedures, while a modified version of the procedure was used in fabricating the temperature-compensation elements.

Preliminary apparent-strain tests of the present method of temperature-compensation at temperatures up to 1,700 °F (927 °C) were performed. The compensated half-bridge outputs were more nearly linear and repeatable, and of less magnitude, than those of the strain gauges in the uncompensated quarter-bridge configuration. Early results indicate that effective cancellation of the effects of temperature-induced changes in the electrical resistance of the active strain gauge and the temperature-compensation element was achieved. Numerous undesired attributes of high-temperature strain gauges used in the quarter-bridge configurations were reduced when thermally compensated by present method (see Figure 2). These attributes include zero shifts (sensor non-return to zero) as a function of cooling rates, rates of drift during static holds, and uncertainties in the phase transformations of gauge alloys.

Two problems observed in bare-wire temperature-compensation elements have also been eliminated using present method. These problems include slope change of the overall apparent-strain curve from one cycle to the next cycle, and excessive drift at high temperatures. A "cycle" refers to both the heat-up and cool-down portion of a test. These changes in slope from cycle-to-cycle and excessive drift rates do not occur in the gauges fabricated and used according to this method because the active gauge and the temperature-compensation element are under the same condition; they are both encapsulated in alumina, therefore, subjected to the same oxidation environment. In contrast, a bare-wire temperature-compensation element oxidizes differently than the active gauge since it is not encapsulated in alumina. In addition, heat conduction will often be quicker to a bare-wire element (lower mass) when compared to the encapsulated active gauge. This temperature lag in the active gauge becomes more pronounced as transient heating rates increase causing the electrical resistance cancellation of the half-bridge to be less effective.

This work was done by Anthony Piazza of **Dryden Flight Research Center.**

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Dryden Flight Research Center [see page 1]. Refer to DRC-96-74.

System for Detecting Hazardous Gases at Multiple Locations

The Hazardous Gas Detection System 2000 (HGDS 2000) is the latest in a series of instrumentation systems for detecting gases leaking from a space shuttle on a launch pad. The HGDS is a fully redundant system that includes analog and digital electronic control circuitry and a subsystem for sampling gases at multiple locations and delivering the samples to two independent commercial quadrupole mass spectrometers. [The sampling subsystem was described in "System for Delivering Gas Samples to Multiple Instruments" (KSC-12123), *NASA Tech Briefs*, Vol. 25, No. 6 (June 2001), page 60.] The system is rugged enough to withstand the launch-pad environment, is easy to operate, and can be fully automated. When in automated operation, the system notifies an operator if an unusual situation or a fault is detected. An operator interacts with the system via a personal computer by use of mouse and keyboard commands. Operation of the HGDS 2000 is expected to take substantially smaller amounts of operators' time and to cost substantially less, relative to operation of the older instrumentation systems in this series. Although the HGDS 2000 is optimized for detecting leaking spacecraft-propellant gases, it can also be used to detect many other gases.

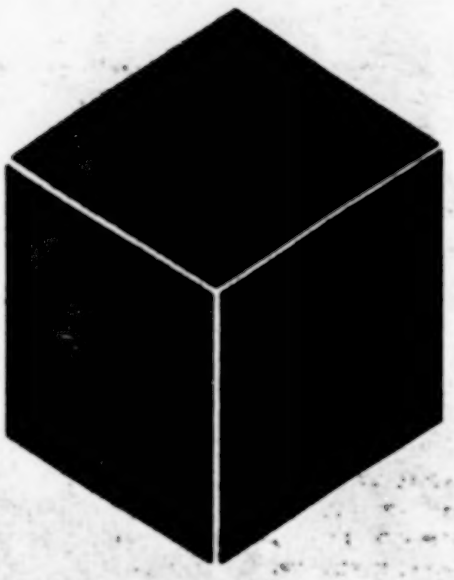
This work was done by Carolyn Mizell and Greg Breznik of **Kennedy Space Center** *and Tim Griffin, Guy Naylor, William Haskell, Richard Hintz, David Floyd, and Charles Curley of Dynacs, Inc.*
KSC-12250

Books and Reports

Narrowband Tunable Optical Filter Using Fiber Bragg Gratings

Research at Langley Research Center has developed a special fiber-Bragg grating optical filter for use in aircraft or spaceborne differential absorption lidar (DIAL) systems for measuring water vapor in the atmosphere of the Earth. The filter is an optical fiber containing two Bragg gratings that afford high reflectance in 10-pm-wide wavelength bands at wavelengths of 946.0 and 949.5 nm. The optical fiber would be glued to a piezoelectric ceramic, to which a voltage could be applied to stretch the gratings and thereby adjust their peak-reflection wavelengths to correspond to atmospheric water vapor lines of interest. The concept of multiple Bragg gratings in a single optical fiber tuning such gratings by stretching the fiber is not new. The novelty of this research lies partly in the application of these concepts to make tunable ultra-narrowband filters for the specific water vapor wavelengths in question. Another element of novelty in the proposal lies in the design of the DIAL instrument in which the filters would be used. The design calls for a unique optical receiver that would couple a lidar signal from a telescope to a filter of the type proposed, then using an optical circulator the light would be detected.

This work was done by Russell DeYoung of **Langley Research Center.** *To obtain a copy of the report, "Ultra-Narrow Passband Optical Filter for Space Water Vapor DIAL Applications," see TSP's [page 1].*
LAR-15978



Materials

Hardware, Techniques, and Processes

Reducing Wear and Friction of CVD Diamond Films

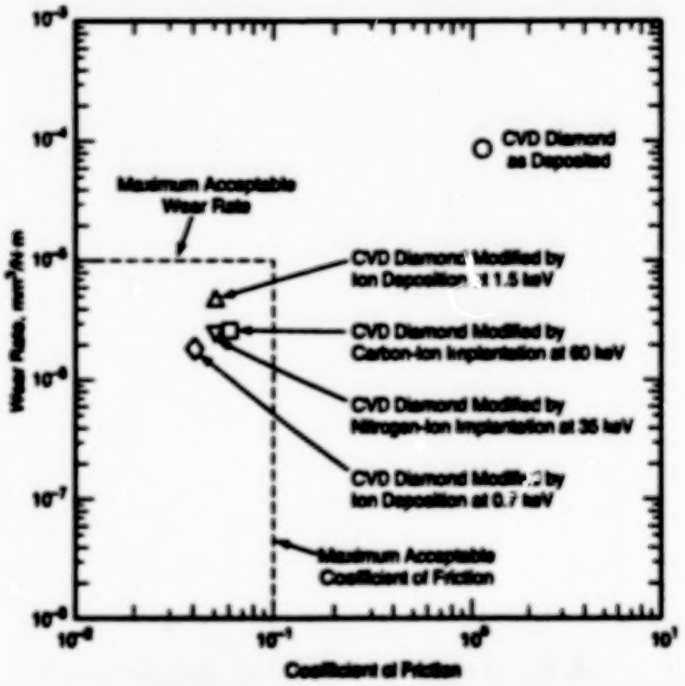
Surface modifications reduce friction and wear, even in ultrahigh vacuum.

John H. Glenn Research Center, Cleveland, Ohio

Progress has been achieved in continuing research directed toward increasing the wear resistance and enhancing the self-lubrication properties of chemical-vapor-deposited (CVD) diamond films. Such films are potentially useful as friction- and wear-reducing coats on sliding mechanical components (e.g., seals, gears, and journal bearings). A major issue that has been addressed in this research is the variation of the friction and wear properties of CVD diamond with environment: In air, CVD diamond exhibits a low coefficient of friction and high resistance to wear; in vacuum, it exhibits a high coefficient of friction and low resistance to wear. In three experimental studies, it was found that friction and wear of CVD diamond films in both vacuum and air can be reduced by use of suitable surface treatments.

In the first study, a fine-grained CVD diamond film in the as-deposited condition was tested in comparison with two similar CVD diamond films that were coated with thin (< 1 μm thick) films of amorphous, non-diamond carbon (more specifically, hydrogenated carbon, also known as diamondlike carbon [DLC]). The DLC coating layers were deposited by direct impacts of ion beams at kinetic energies of 1.5 keV and 0.7 keV, respectively. In tribological tests (diamond-tipped pins sliding on disks coated with the various CVD diamond films) at room temperature in ultrahigh vacuum, the DLC films were found to reduce the coefficient of friction and the wear rate significantly (see figure).

The second study was similar to the first study. Fine-grained CVD diamond films were modified by implantation of, variously, carbon ions at a kinetic energy of 60 keV or nitrogen ions at a kinetic energy of 35 keV. In both cases, the implantation resulted in the formation of amorphous, non-diamond carbon surface layers <1 μm thick. As in the first study, the modification of the as-deposited CVD diamond reduced the coefficient of friction and the wear rate significantly.



Wear Rates and Coefficients of Friction of as-deposited and modified CVD diamond films were measured in ultrahigh vacuum. The results plotted here indicate that suitably modified CVD diamond films could be useful as wear-resistant, self-lubricating surface layers on sliding mechanical components.

The subject matter of the first and second studies overlaps with that of a prior study reported in "Ion-Beam-Deposited DLC Coatings on Fine-Grain CVD Diamond" (LEW-16584), *NASA Tech Briefs*, July 1998. The third study addressed the issue of a friction- and wear-resistant couple of materials; that is, a pair of materials that exhibit low friction and low wear when slid against each other. This study included ultrahigh-vacuum tests in which CVD-diamond-tipped pins were slid against a disk coated with cubic boron nitride films. The wear rate of the boron nitride films was found to be acceptably low (of the order of 10^{-6} $mm^3/N\cdot m$), the wear rate of the diamond films was found to be much lower, and the coefficient of friction was found to be very low (of the order of 0.02).

This work was done by Kazuhisa Miyoshi of Glenn Research Center. Further information is contained in a TSP (see page 1).

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17150.

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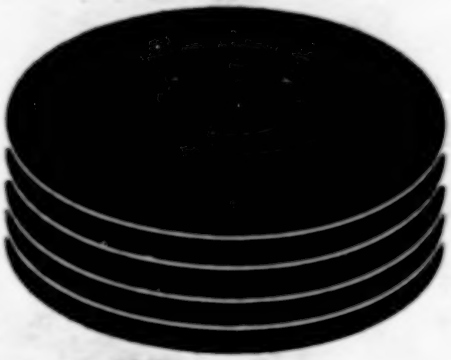

Computer Programs

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Electronic Components and Circuits

Program Analyzes Current Signatures of Solenoid Valves

A computer program processes signal data in the instrument described in "Current-Signature Sensor for Diagnosing Solenoid Valves" (KSC-12152), *NASA Tech Briefs*, September 2001. Ten-bit samples of the electric current in a solenoid valve are acquired at a rate of 10 kHz and fed to a digital signal processor that executes the present software, which performs buffering, filtering, identification of features, and general assessment of the "health" of the valve. The identified signal features include the time of beginning of a transition, the time of maximum change in current, the time when the poppet begins to move, the amplitude of the current needed to initiate movement, the time of travel of the poppet to final seating, the time when the current reaches the steady state, the amplitude of the steady-state current, the minimum current needed to hold the poppet against unseating, and the time required for the poppet to unseat. The software can generate indications of impediment or jamming of the poppet; burnt or short-circuited solenoid windings; buildup of friction; faulty valve spring; incorrect operating voltage, temperature, or pressure; bounce during seating of the poppet; and failure of anti-arcing circuitry.

This program was written by Bradley M. Burns of Dynacs, Inc., for **Kennedy Space Center**. *Further information is contained in a TSP [see page 1].*
KSC-12220

Physical Sciences

Program Predicts Radiation Forces on a Satellite

A computer program predicts the radiation forces on the TOPEX/Poseidon satellite at any point in its orbit around the Earth. The program performs a unified analysis of the thermal, radiative, power-generation, and orbital-mechanics aspects of operation because these aspects are interdependent: The power-generating capacity of the solar panel of the satellite depends on both the impinging radiation and its temperature, which, in turn depends on both its power output and the radiative environment. The radiative environment depends on the trajectory and attitude of the satellite relative to the positions of the Earth and Sun. Only by considering all of the aforementioned phenomena together can one predict the temperature and power generation of the solar panel and the battery charges, currents, and voltages. Then the radiation forces are calculated from the results of the foregoing unified thermal/power/radiative analysis. Output is available in two forms: (1) a tabulation of all components of radiative forces over a single orbit, based on the day of the year and the relative orientations of the Sun, Earth, and orbit; and (2) a tabulation of the average radiation forces over a single orbit for any number of specified beta prime angles and the corresponding days of the year.

The unified analysis was developed and this program was written by Robert Richter of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP [see page 1].*

This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. Refer to NPO-21019.

Mathematics and Information Sciences

Software Generates Sequences of Operations for a Mars Rover

Automated Rover Sequence Generation (ARSG) is a prototype computer program for ground-based automatic generation of sequences of commands that can be used for a robotic exploratory vehicle (rover) on Mars. ARSG is based on the Automated Scheduling and Planning Environment (ASPEN) computer program, which has been described in several *NASA Tech Briefs* articles in recent years. Given high-level scientific and engineering activities required of a rover, ARSG automatically generates a sequence of commands that can be executed by the rover within resource constraints and in compliance with flight rules. An automated-planning-and-scheduling software subsystem encodes rover design knowledge and uses search and reasoning techniques to automatically generate low-level command sequences while (1) respecting rover operability constraints, scientific and engineering preferences, environmental predictions, and (2) adhering to hard temporal constraints. By enabling goal-driven command of planetary rovers, this software can reduce the need for highly skilled rover engineering personnel, thereby reducing the costs of mission operations. ARSG enables faster responses to changes in the state of a rover (e.g., malfunctions) or to scientific discoveries by eliminating the time-consuming manual validation of command sequences and enabling rapid "what-if" analyses.

Contributors to this software include Robert Sherwood, Tara Estlin, Darren Mutz, Gregg Rabideau, Steve Chien, Paul Backes, Jeff Norris, Brian Cooper, and Scott Maxwell of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP [see page 1].*

This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. Refer to NPO-30204.

OwWwL and AgentNation: Knowledge-Robot Software

OwWwL and AgentNation are Java-language computer programs that act together, quickly scanning Internet databases for relevant information, then organizing the information into a format suited to the user. OwWwL is a search-engine program that, like other such programs, includes a "spider" subprogram that "crawls" the Web, indexing content. AgentNation is a collaborative-computing program that is used by OwWwL to perform its tasks in a collaborative manner; that is, OwWwL and AgentNation can be run simultaneously on multiple computers to perform large-scale searches. The biggest difference between OwWwL and other search-engine programs is that as the OwWwL spider subprogram performs a search on a given topic, it begins to search for related information. OwWwL includes a personal-search-assistant subprogram that with the help of AgentNation, searches other Internet search engines simultaneously.

This program was written by Joseph L. Nieten and Dan Dexter of LinCom for

Johnson Space Center. *Further information is contained in a TSP [see page 1].*

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

LinCom
1020 Bay Area Blvd.
Suite 200
Houston, TX 77058

Refer to MSC-23063, volume and number of this NASA Tech Briefs issue, and the page number.

Web-Based Software Service Improves Space-Shuttle Processing

Human data-transfer from space-shuttle checkout systems to shuttle business systems is slow, error-prone, and expensive. The Operations and Maintenance Requirement Specification-Automated Buy Off System (OMRS-ABOS) is a software system that automatically transfers test-validation data produced by Kennedy Space Center's Checkout and Launch Control System (KSC's CLCS) for the space shuttle, to its Integrated Work Control System (IWCS). The test-validation data includes pass/fail results from equipment tests required by a set OMRSs. While other commercial-off-the-shelf (COTS) approaches require existing work forces to change their business practices, OMRS-ABOS utilized a COTS approach that preserved KSC business practices. The OMRS-ABOS implemented commercial Enterprise Application Integration (EAI) software development practices, deployed to an *n*-tier software architecture, and utilized Java 2 Enterprise Edition (J2EE). The COTS software platform saved time and expenses while infusing state-of-the-industry technologies. OMRS-ABOS provides a channel for KSC enterprise shuttle checkout systems to transfer OMRS events to IWCS. The Remote Manipulator System (RMS) Checkout System is the latest to automate its transfer of OMRS-event data. OMRS-ABOS' latest improvement includes distributed data communications made available by the eXtensible Markup Language (XML). By utilizing XML as a data transport vehicle, OMRS-ABOS may communicate more easily with commercial enterprise platforms.

This work was done by Todd Rato, Keith Heob, and Barry Rubel of Riptide Software Incorporated and Kevin Smith of **Kennedy Space Center**.

This technology is available for commercial licensing. Please contact Barry Rubel of Riptide Software Incorporated at (321) 427-5694. Refer to KSC-12312.

Application Fault Injector

Application Fault Injector (AFI) is a simple computer program for testing the fault tolerance of other programs. AFI is a library of subroutines designed to inject faults into memory, data structures, and registers. The library is modular, can easily be extended, and can easily be ported to different computer hardware architectures. AFI is not designed to run fault-injection campaigns on complete application programs; instead, it is designed to test fault-tolerant algorithms, subroutines, and data structures. AFI is easy to use. The application programmer has complete control of fault injection.

This program was written by Thomas Wolle of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP [see page 1].*

This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. Refer to NPO-30344.

Machinery

Hardware, Techniques, and Processes

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Internal-Combustion Engines With Ringless Carbon Pistons

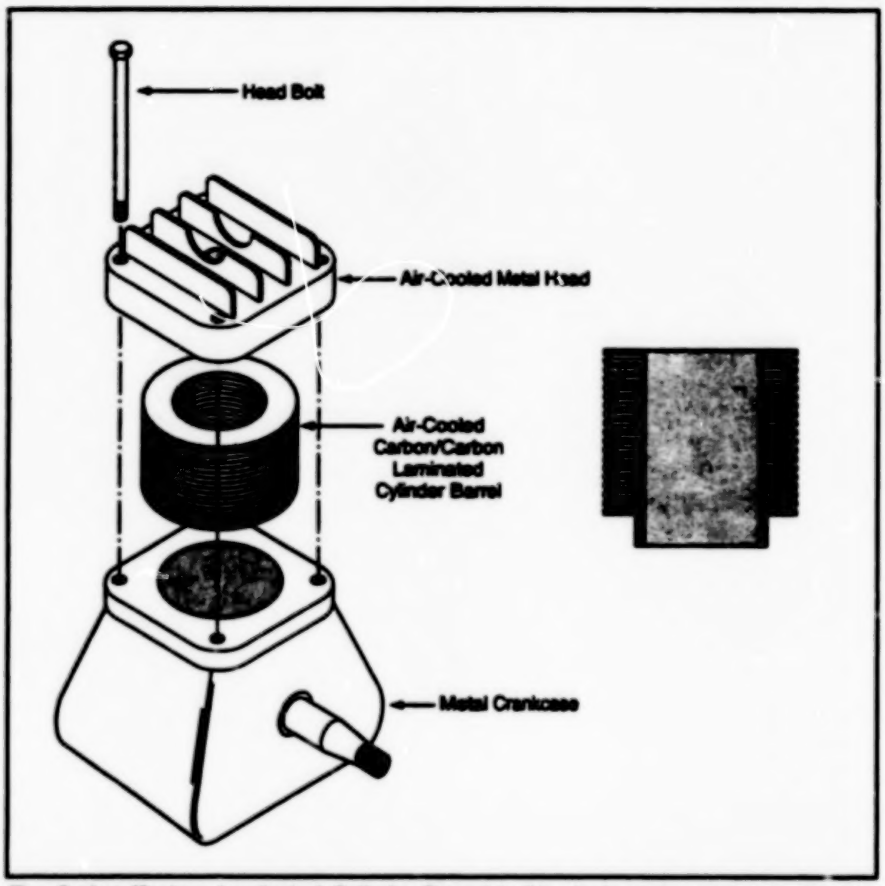
Efficiencies would be higher and weights lower than those of conventional engines.

Langley Research Center, Hampton, Virginia

Internal-combustion engines would be constructed with cylinders and ringless pistons made of lightweight carbon/carbon composite materials, according to a proposal. This proposal is a logical extension of previous research that showed that engines that contain carbon/carbon pistons with conventional metal piston rings running in conventional metal cylinders perform better than do engines with conventional aluminum-alloy pistons. The observed performance improvement (measured as increased piston life during high-performance operation) can be attributed mainly to the low thermal expansion of the carbon-carbon composite. Carbon-carbon pistons can continue to operate under thermal loads that cause aluminum pistons to seize or sustain scuffing damage due to excessive thermal growth and thermal distortion.

In addition to having an extremely low coefficient of thermal expansion, carbon-carbon is about 30 percent lighter than aluminum which provides the benefit of reduced reciprocating mass (lower reciprocating mass can potentially reduce vibration forces and increase r/min. capability). Carbon-carbon composite also has the advantage over aluminum that it fully retains room-temperature strength and stiffness at high temperatures. Furthermore, the strength, thermal expansion, and thermal conductivity of carbon-carbon composites can be tailored by orientation of the carbon fibers and selection of fiber type, matrix type, and processing methods.

The rings are needed on aluminum pistons to seal the clearance which must exist between the piston and cylinder wall to accommodate differential thermal expansions of the piston and cylinder material (conventionally, a cast iron sleeve in an aluminum block). Although cold-clearance can be reduced somewhat by substituting a carbon-carbon piston, rings will still be needed to obtain effective sealing. An advantage is potentially achievable in a four-stroke engine because a tighter piston fit reduces the so-called "crevice volume" or the gap between the piston and the cylinder wall above the top ring. Fuel mixture which enters this gap is not combusted and is exhausted as unburned hydrocarbon. If the metal block were to be fitted with a carbon-carbon sleeve, the cold clearance could be further reduced, but minimum clearance might be difficult to achieve because the sleeve shape could be affected by thermally-induced distortions in the surrounding metal block (there are also issues as to how the sleeve might be contained in the block). If, on the other hand, the metal cylinder block and sleeve were to be replaced with a cylinder block made entirely of carbon-carbon, the thermal expansion differential between the piston and cylinder materials would virtually be eliminated, as would the potential for thermal distortion of either component. The clearance could then be reduced to the absolute minimum. Operation without rings, which would eliminate a source of power-robbing friction, can now be considered an intriguing possibility. Rings may ultimately be required in the four-stroke application to minimize combustion-gas blow-by and/or control oil consumption; however, the crevice volume, which is a major cause of hydrocarbon emissions, would be eliminated over the engine's entire operating temperature range and ring performance could potentially be improved because of less piston rocking in the bore. Ringless operation would appear to be particularly attractive for high-r/min two-stroke engines where oil-wiper rings are not required and relatively more blow-by may be tolerable.



The Carbon/Carbon Laminated Cylinder Barrel in this single-piston engine (or the carbon/carbon laminated cylinder block in a multiple-piston engine) would house a ringless carbon/carbon piston.

For simplicity, the figure illustrates a one-cylinder, air-cooled, two-stroke internal-combustion engine that might be built according to this concept (multicylinder and four-stroke engines are also possible). The cylinder barrel would be made of carbon-carbon composite sandwiched between an air-cooled metal head and a metal crankcase. This assembly would be held together by long head bolts, which would pass through the head and through (or alongside) the carbon/carbon cylinder barrel into threaded holes in the crankcase. The carbon/carbon cylinder barrel could be sealed to the crankcase with an O-ring and to the head with a head gasket.

The cylinder block could be fabricated with one or more of many possible configurations of fibers in the carbon/carbon material. The simplest and most economical configuration would be a stack of plies in which all fibers are aligned perpendicular to the axis of the cylinder bore. The inherently low interlaminar strength of the carbon/carbon block would not be a major concern because the clamping force applied by the head bolts would negate cross-ply tensile stresses in the laminate. In principle, this configuration could likely be chosen to maintain the close-tolerance piston/cylinder clearance because it would exploit two features of carbon fibers that are very attractive in this application: high lengthwise thermal conductivity (for some fibers, greater than that of copper) and nearly zero lengthwise thermal expansion. This configuration would minimize thermal expansion of the cylinder bore while maximizing the outward conduction of heat through the cylinder barrel to the ambient air. In practice, some circumferentially oriented fibers would also be needed to provide reinforcement against hoop stresses, but the proportion of such fibers should be minimized.

Fabrication of the cylinder barrel could begin with stacking the plies in a mold that could include an inner mold die roughly the size of the cylinder bore. Alternatively, the cylinder bore could be machined somewhat undersize prior to carbonization. In either case, the initial formation of the bore would expose the inner edges of all the plies to impregnating materials, which would be applied during densification steps. Eventually, the cylinder bore would be machined to near the final diameter, then the inner surface of the cylinder would be treated in sealing and coating processes to reduce friction and protect against oxidation. The cylinder would then be honed to its final diameter.

This work was done by Philip O. Ransone of **Langley Research Center**. *No further documentation is available.*

This invention is owned by NASA, and a patent application has been filed. Inquiries concerning nonexclusive or exclusive license for its commercial development should be addressed to the Patent Counsel, Langley Research Center [see page 1]. Refer to LAR-15094.

Advances in Cooperative Transport by Two Mobile Robots

Two mobile robots move in formation while transporting a long payload.

NASA's Jet Propulsion Laboratory, Pasadena, California

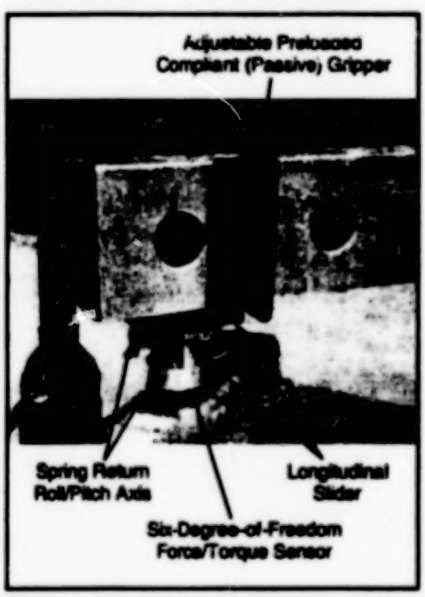


Figure 1. The Gimbal Mechanism enables the gripper to move freely in one translational and three rotational degrees of freedom, and measures forces and torques.

Figure 2. Two Mars Rovers transport a long payload in diagonal formation.

Special gimbal mechanisms and algorithms that implement decentralized compliant control have been developed for use in research on the sensors, the actuators, and the design and functional requirements for systems of multiple mobile robots cooperating in site-clearance and construction operations. The gimbal mechanisms and control algorithms were designed, in particular, to enable two robotic exploratory vehicles (i.e., rovers) to transport a long payload while moving along the ground in a commanded formation. Although these developments are parts of a continuing effort to develop robotic capabilities for exploration of Mars, the same robotic capabilities could be expected to find application on Earth.

Each gimbal mechanism (see Figure 1) has four degrees of freedom. One such mechanism is part of each rover. The gimbal incorporates a compliant gripper on a longitudinal slider for "soft grip" of a payload. The gimbal is passive and is fully instrumented with potentiometers to measure the orientation and position (pitch, roll, yaw, and lateral translation) of the gripper. The gimbal mechanism is mounted on a six-degree-of-freedom load cell, which is used to resolve reaction forces. The load cell, in turn, is mounted on a cross brace between shoulders of the robotic vehicle.

The decentralized compliant control scheme uses no explicit communications; i.e., the rovers do not "talk" to each other via wireless modems but communicate with each other implicitly via their common payload through force sensors. The

scheme involves four low-level behaviors denoted *formation controller*, *minimize forces/torques on payload*, *center payload in longitudinal slider*, and *group formation*. The control inputs for three of the behaviors are the speed and heading of a rover. The *formation controller* behavior receives a formation-angle command from the *group formation* behavior. The commanded formation angle is mapped to the corresponding gimbal yaw angles on the two rovers. The *formation controller* behavior then seeks to control the speed and heading of each rover in an effort to achieve and maintain the commanded gimbal yaw angle on each rover.

The *minimize forces/torques on payload* behavior seeks to minimize the forces on the payload or compliant linkage on each rover. The forces on the payload can be high if the relative speed between the two rovers is greater than a set threshold. The magnitude of the force along the longitudinal axis of the payload is the input for this behavior. The predominant control output of the *minimize forces/torques on payload* behavior is a rover speed command, supplemented with steering-correction commands.

The *center payload in longitudinal slider* behavior seeks to minimize deviations of the payload from midpoint of the longitudinal slider on each rover. The control outputs of the *center payload in longitudinal slider* behavior are a rover-speed and heading (steering) control command.

Proportional-plus-derivative (PD) controllers for speed and heading modifications that satisfy the requirements for the *formation controller* and *center payload in longitudinal slider* behaviors under steady-state conditions have been developed. The PD controllers independently achieve their respective goals, but when implemented simultaneously, they give conflicting speed and heading corrections. To resolve these conflicts, the outputs of the PD controllers are combined by use of a weighting scheme to compute speed and heading corrections for each rover.

In several experiments performed at Arroyo Seco in Pasadena, California, the following actions were demonstrated:

- A pair of Mars rovers compliantly coupled to a common payload (see Figure 2) autonomously moved, variously, forward or backward through distances of 5 to 50 m over uneven, natural terrain.
- The pair of rovers compliantly coupled to a common payload autonomously changed formations between arbitrary initial and final formations (including row, column, and diagonal formations).

This work was done by Ashley Trebi-Ollennu, Hari Das, Anthony Ganino, Hrand Aghazarian, and Brett Kennedy of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP* *(see page 1).*

NPO-30976

Modular, Highly Maintainable, and Flexible Control Software

This software also lends itself to multitasking and distributed processing.

Marshall Space Flight Center, Alabama

Modal Rocket Engine Software System (MRECS) is a system of control software that was originally intended for use in controlling rocket engines but is also applicable to almost any real-time, closed-loop process-control system — for example, the feedback control system of a robot. MRECS affords the capabilities necessary for feedback control, actuation of valves and other devices by use of discrete and/or analog commands, processing of sensor readings, and generation of alarms by comparison of various quantities with limiting values. MRECS is capable of real-time multitasking and is amenable to distributed processing. It is designed, from the outset, to be highly maintainable and to be flexible in the sense that, in response to changing requirements, it can be quickly and reliably modified and tested.

In previous efforts to develop rocket-engine-control software, there was an emphasis on minimizing the costs of development. However, the costs of maintenance and operations are significant parts of total life-cycle costs. In the development of MRECS, there has been less emphasis on limiting the cost of development and more emphasis on utilizing modularity and flexibility to reduce the costs of maintenance and operations.

MRECS takes advantage of the inherent support for modularity in the Ada programming language to implement real-time multitasking. Of all the engine-control programs in the experience of personnel at Marshall Space Flight Center, MRECS is the first to use real-time, preemptive priority-scheduled multitasking, the first to run on a commercial off-the-shelf (COTS) real-time operating system, and the first to use the standard Transmission Control Protocol/Internet Protocol (TCP/IP) for both command input and telemetry output. Through the use of Ada and COTS system software, MRECS has been made transportable to a variety of state-of-the-art computers and operating systems. In use, the worth of MRECS has been proven in that MRECS has been shown to be adaptable to different engine configurations and characteristics, to be amenable to rapid modification, and to perform engine-control functions reliably.

This work was done by Robert L. Stevens and Richard H. Beckham of **Marshall Space Flight Center**.

MFS-31417

Magnetostrictive Motor and Circuits for Robotic Applications

Notable features include power-factor correction, speed control, and high position resolution.

Lyndon B. Johnson Space Center, Houston, Texas

A magnetostrictive motor and its drive circuit and control system have been designed to be especially suitable for robotic applications in which there are requirements for precise, high-force linear actuators. The motor includes a laminated armature made of the magnetostrictive alloy $Tb_{0.27}Dy_{0.73}Fe_{2}$. The armature is sandwiched between two double-layered, three-phase stators, which are energized to make the armature move linearly in "inchworm" fashion. The total range of linear motion is 25 mm. Like other magnetostrictive motors, this motor offers the advantages (relative to geared-down conventional motors) of reduced weight, extreme ruggedness, fewer moving parts, greater reliability, and self braking when power is not applied.

A capacitor is connected in series with the stator windings to correct the power factor. This or almost any other magnetostrictive

motor presents a highly inductive load to its drive circuit and therefore operates at a low power factor in the absence of correction. As in other electrical applications, a low power factor is undesirable because it gives rise to the need for a greater drive potential or drive current than would otherwise be needed to deliver a given amount of power. At its resonance frequency of 470 Hz, the motor windings exhibit a power factor of 0.352, but the series combination of the capacitor and the motor windings exhibits a power factor of 0.989 — close to the ideal value of 1.

Because the speed of the inchworm motion depends on both the amplitude and frequency of the drive current, the control system includes one controller that holds the frequency constant and varies the amplitude and another controller that holds the amplitude constant and varies the frequency. Both controllers utilize proportional + integral compensation and implement an integrator-antiwindup scheme to limit accumulation of position-error signals.

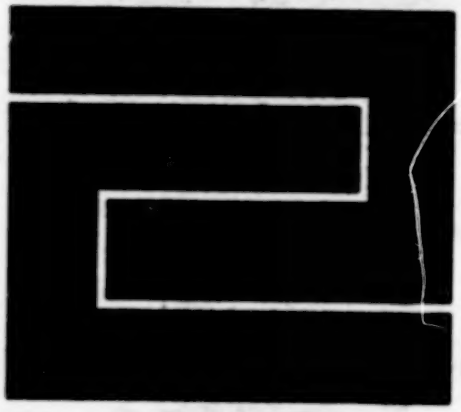
The control system includes a position sensor and a 12-bit analog-to-digital (A/D) converter that processes the sensor output. Because the output swing of the position sensor is only one quarter of the input range of the A/D converter, one could utilize only 10 of the 12 bits (corresponding to a position resolution of 49 μm) if one were to feed the raw sensor output to the converter. Therefore, to make use of full 12-bit resolution of the A/D converter, the sensor output is fed to the converter via an amplifier stage gain of 4. Another amplifier stage with a gain of 39 is also included to demonstrate a capability of precise positioning; a position resolution of ≈1.25 μm is achievable when this amplifier is included in the signal path.

This work was done by James H. Goldie, Won-Jong Kim, Andrew E. Barnett, and William R. Snow of SatCon Technology Corp. for **Johnson Space Center.** *Further information is contained in a TSP [see page 1].*
MSC-23051

Water-Jet Accelerator for Launching a Spacecraft

A proposed ground-based apparatus would accelerate a spacecraft to speed of about mach 1, thus making it possible to increase the payload and/or reduce the cost of launching the spacecraft into orbit. The apparatus would include a track along which the spacecraft would ride on a sled. Hundreds of small water jets energized by compressed-air packs would be located under, and at small intervals along, the track. Each jet would be activated in turn as the sled passed by, aiming a high-speed (possibly supersonic) stream of water at baffles on the underside of the sled. The force of water impinging on the baffles would provide levitation and accelerate the sled along the track. Unlike a previously proposed launch-assisting linear electric motor, the water-jet apparatus would function without need for expensive electric-power-conditioning equipment. Unlike another launch-assist concept involving a piston driven along a pneumatic tube, the present concept does not present problems of how to (1) couple the piston to the sled and (2) exert fine control over acceleration. Another advantage of the water-jet concept is redundancy: even if several water jets were to malfunction, the remaining many functional water jets should suffice.

This work was done by Robert Youngquist and Frederick Adams of **Kennedy Space Center.**
KSC-12257



Fabrication Technology

Hardware, Techniques, and Processes

Low-Plasticity Burnishing

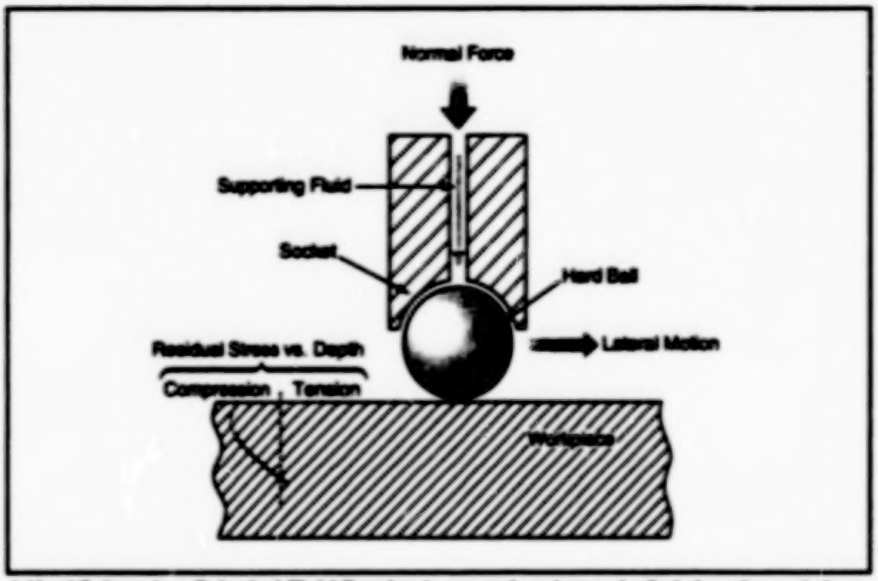
Fatigue life and resistance to damage are increased at relatively low cost.

John H. Glenn Research Center, Cleveland, Ohio

Low-plasticity burnishing (LPB) has been developed as an affordable means of imparting residual compressive stresses to surface layers of metal parts (especially engine components) in order to increase their fatigue lives. Heretofore, surface compressive stresses to enhance the fatigue lives have been produced, variously, by shot peening or laser shock peening. Unfortunately, thermal relaxation has been found to result in loss of the needed surface-layer compressive stresses, with consequent shortening of component lives and reduction of engine performances. Hence, what is needed is a means of imparting thermally stable surface compression.

In the LPB process, a smooth, free-rolling spherical ball is pressed against and rolled along the surface of the workpiece to be burnished. The ball must be hard, and it must have a high modulus of elasticity and a high yield strength. To ensure free rolling, the ball is supported in a spherical-socket fluid bearing (see figure) with sufficient fluid pressure and flow to maintain the ball out of contact with the socket. The force with which the ball is pressed against the surface is made large enough to deform a surface layer of material into a state of compression, taking account of any tensile stress that might exist in the workpiece prior to burnishing.

By use of the positioning capability of a computer numerically controlled (CNC) machine tool, the ball is moved along the surface in a raster or other suitable pattern to cover the surface in a series of passes at a controlled separation chosen to obtain maximum compression with minimum cold working. LPB is not limited to flat workpieces: In the case of a complexly shaped workpiece, the positioning capability of a multiaxis CNC machine tool can be exploited to move the ball on any desired path across the surface, as in a typical multiaxis CNC machining operation.



A Hard Sphere in a Spherical Fluid Bearing is pressed against and rolled along the workpiece, deforming a surface layer into a state of compression.

LPB produces minimal cold work, imparting greater (in comparison with shot peening and laser shock peening when performed with multiple shocking cycles) resistance to thermal relaxation at high temperature. The resulting greater retention of surface compression at engine operating temperatures results in substantial increases in fatigue lives and in retardance of the growth of pre-existing cracks. In addition, LPB increases resistance to damage by impacts of foreign objects.

LPB costs less than does laser shock peening and offers greater depth and stability of the compressive layer, relative to shot peening. Because LPB can be performed easily during manufacturing by use of conventional CNC machine tools, there is no need to ship components to separate facilities for LPB. The process can be readily accommodated in an existing machine shop environment. Both the capital cost of LPB equipment and the unit cost of component processing typically are an order magnitude less than for laser shock peening.

This work was done by Paul S. Prevey III of Lambda Research for Glenn Research Center. Technical assistance was provided by Glenn researchers of the Material Division and Structures Division, working on the ULTRASAFE PROJECT'S Crack Resistant Disk Material: SUB-PROJECT. Further information is contained in a TSP [see page 1].

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17188.

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Mathematics and Information Sciences

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Windowed Revocation of Public-Key-Encryption Certificates

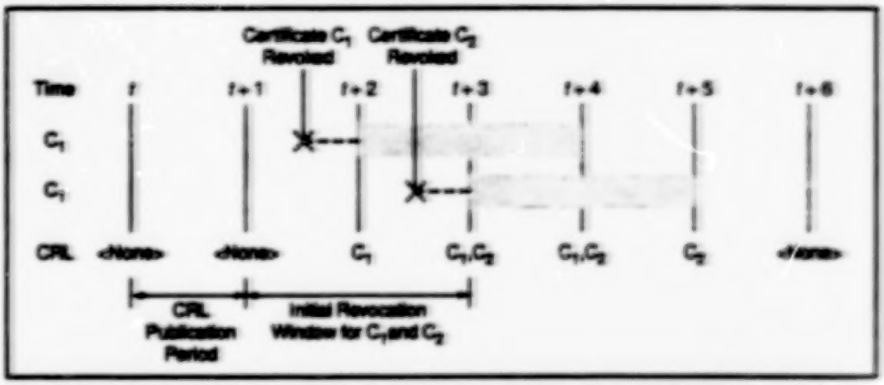
The costs of computation and communication are less than in prior certificate-revocation techniques.

John F. Kennedy Space Center, Florida

Windowed revocation is a technique for the revocation of the digital certificates that provide assurance of the authenticity and integrity of public encryption keys and associated private decryption keys. These keys are used to protect the privacy of communications via the Internet. The need for revocation of certificates arises in cases in which private keys are lost or compromised, rights of access are changed, or it is desired to change keys as a precaution against cryptanalysis. Windowed revocation satisfies the security requirements and conforms to the policies of public-key systems now in use, while imposing less (relative to prior certificate-revocation techniques) of a burden on certificate server computers and communication networks.

Heretofore, the acceptance of certificate-distribution services has been inhibited by the lack of a certificate-revocation technique that is scalable in the sense that the cost associated with the management, retrieval, and verification of certificates would increase at a rate less than the rate of growth of the community served. There are two fundamental approaches to the distribution of information about revocation of certificates: explicit and implicit.

- In certificate-distribution architectures that employ explicit revocation, each issuer explicitly states which certificates are revoked, and indirectly which are not revoked. In systems based on the X.500 standard, each issuer periodically generates a list of certificates that have been revoked but have not yet expired. The presence of the certificate in the list, called a certificate revocation list (CRL), explicitly states revocation. The performances of such systems are largely limited by the cost of bandwidth: the transmission of large CRLs to potentially many clients can be prohibitively expensive.
- In certificate-distribution architectures that employ implicit revocation, lack of revocation is asserted implicitly through the verifier's ability to retrieve the certificate. Any certificate retrieved from the issuer is guaranteed to be valid at or near the time of retrieval. Associated with each certificate is a time to live (TTL), which represents the maximum time the certificate may be cached. Thus, in implicit revocation, the window of vulnerability is the TTL. The performance of a system that uses implicit revocation is limited by the cost of acquiring certificates: supplying real-time information on revocation status during each acquisition is computationally expensive.



This Time Line Illustrates an example of windowed revocation. Once certificates C_1 and C_2 are revoked, they are mentioned in CRLs that occur during their revocation windows.

Windowed revocation involves a hybrid of explicit and implicit revocation that affords the desired scalability. In windowed revocation, the issuer asserts revocation in two different ways at two different times: (1) implicitly during initial acquisition of a certificate, and thereafter (2) explicitly through periodically published CRLs. Verifiers acquire CRLs from issuers directly. Retrieved certificates are guaranteed to be nonrevoked, fresh, and authentic. Subsequent validation of the revocation statuses of certificates is effected primarily through CRLs.

CRLs are generated at uniform time intervals, each interval being denoted a CRL publication period. Revoked certificates are mentioned in the CRLs that occur during possibly longer intervals denoted revocation windows (see figure). A revocation window is the time during which a certificate may be cached without further validation. The revocation window is specified by the issuer and documented in each certificate. By bounding the times during which each revoked certificate must be included in the periodic CRLs, revocation windows limit the sizes of CRLs and thus the costs of distributing them.

Windowed revocation is secure, and its correctness has been rigorously mathematically proved. In worst-case situations, it requires no more network bandwidth than do prior CRL-based techniques and no more central-processing-unit resources than do prior implicit techniques. Moreover, the tradeoffs between consumption of resources and security can be managed through the parameters of windowed-revocation protocols.

This work was done by Sugih Jamin and Patrick D. McDaniel of the University of Michigan at Ann Arbor for **Kennedy Space Center.**

In accordance with Public Law 96-517, the contractor has elected to retain title to this invention. Inquiries concerning rights for its commercial use should be addressed to

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Refer to KSC-12149/12208, volume and number of this NASA Tech Briefs issue, and the page number.

Books and Reports

Technical Background of Special Bus-Driver Software

A short report discusses the technical background of, and the need for, special bus-driver software for part of a test-bed computer system that is to be used in experimentation for development of advanced avionics. The system features a scalable, fault-tolerant, distributed architecture that incorporates a variety of commercial standard bus interfaces. The special bus-driver software is needed to overcome an incompatibility between (1) a Power PC 750 processor made by a first manufacturer and (2) an IEEE 1394 bus-interface circuit board made by a second manufacturer for use in conjunction with a different version of

the Power PC 750 made by a third manufacturer. The hardware-related portions of source code of the driver software of the IEEE 1394 board from the second manufacturer was modified and ported to the power PC 750 processor from the first manufacturer. The source code as thus modified has been found to perform successfully and is now in use in the test bed.

This work was done by Minh Lang, Savio Chau, and Tom Huynh of Caltech for **NASA's Jet Propulsion Laboratory**. *To obtain a copy of the report, "IEEE 1394 bus driver software for the Synergy Power PC 750 processor," see TSP's [page 1].*

This software is available for commercial licensing. Please contact Don Hart of the California Institute of Technology at (818) 393-3425. Refer to NPO-30284.

END

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